

Demonstration of Nautilus Centripetal Capillary Condenser Technology

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This paper describes the results of a proof of concept effort for development of a Nautilus Centripetal Capillary Condenser (NCCC or NC³) used for microgravity compatible water recovery from moist air with integral passive phase separation. Removal of liquid condensate from the air stream exiting a condenser is readily performed here on Earth. In order to perform this function in space however, without gravity or mechanical action, other tactics including utilization of inertial, drag and capillary forces are required. Within the NC³, liquid water forms via condensation on cold condenser surfaces as humid air passes along multiple spiral channels, each in its own plane, all together forming a stacked plate assembly. Non-mechanical inertial forces are employed to transfer condensate, as it forms, via centripetal action to the outer perimeter of each channel. A V-shaped groove, constructed on this outer edge of the spiral channel, increases local capillary forces thereby retaining the liquid. Air drag then pulls the liquid along to a collection region near the center of the device. Dry air produced by each parallel spiral channel is combined in a common orthogonal, out-of-plane conduit passing down the axial center of the stacked device. Similarly, the parallel condensate streams are combined and removed from the condenser/separator through yet another out-of-plane axial conduit. NC³ is an integration of conventional finned condenser operation, combined with static phase separation and capillary transport phenomena. A Mars' transit mission would be a logical application for this technology where gravity is absent and the use of vibrating, energy-intensive, motor-driven centrifugal separators is undesired. Here a vapor stream from either the Heat Melt Compactor or the Carbon dioxide Reduction Assembly, for example, would be dried to a dew point of 10 °C using a passive NC³ condenser/separator with the precious water condensate recycled to the water bus.

2-D	=	two-dimensional
3-D	=	three-dimensional
CNC	=	Computer Numerical Controlled
°C	=	degrees Celsius
g	=	gram
in	=	inches
SLPM	=	Standard Liters Per Minute
min	=	minute
mL	=	milli-Liters
NCCC or NC ³	=	Nautilus Centripetal Capillary Condenser
SBIR	=	Small Business Innovative Research

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I. Introduction

AN SBIR Phase 1 project was conducted June to December of 2015 to demonstrate the conceptual feasibility of a novel Nautilus Centripetal Capillary Condenser (NC³) technology [1]. The ultimate aim of our work was to create a device that operates in a low gravity environment (such as, would be experienced during a Mars transit mission) to effectively dry a hot, moist airstream to a dew point of ≤ 10 °C while separating the gas and liquid product phases, with no liquid water entrainment in the effluent air.

Spiral separator cell patterns cut into silicone rubber sheets and captured between two plates proved fundamental feasibility of the NC³ technology at atmospheric pressure over a range of operating conditions for the primary functions of separation and condensation. Channel cross section dimensions of 0.125 inches deep and 0.625 inches wide coupled with path curvatures above 0.67 in^{-1} ($= 1/r = 1/1.5\text{ in}$) provided good centripetal driven separation and dew point reduction to below 10 °C for air flows between 2 and 7 SLPM at a water input rate between 15 and 30 mL/min.

NC³ circular separators fabricated in a pair of sandwiched 0.0625 inch thick aluminum sheets with a separation channel outer diameter of 5 inches, further refined our understanding of the requirements for good phase separation. Following application of a layer of hydrophobic silicone gasket material filling the 90° corner along the inner edge of the circular path, subsequent testing demonstrated perfect 100% water separation over the full range of air and water flows tested (0-7 SLPM air and 15-30 mL/min water).

Final experiments with an integrated NC³ device repeated the same good condensation and separation performances observed for earlier devices that demonstrated each aspect alone. Most importantly, this fully functional apparatus maintained an exit air dew point below the targeted maximum of 10 °C while achieving complete condensate water separation for air flows above 1 SLPM. This was accomplished while operating at a ~20% scale of that required to process the peak water production for NASA's Heat Melt Compactor as employed aboard a manned transit mission to/from Mars.

Lastly, with application of lessons learned during testing, advanced designs were prepared for future fabrication and evaluation in a Phase II level of effort. These NC³ designs are multi-channel condenser/separator constructs formed in two ways: i) using multiple stacked parallel plates; as well as, ii) using 3-D printing techniques.

II. Background

The separation of air and water is a necessary operation for human spaceflight life support. There are many concepts in various stages of development for NASA applications. The ultimate goal is to prepare for a future crewed mission to Mars. One of these concepts, or a combination, might be down-selected for application to crew cabin air revitalization, water recovery from astronaut trash, and other life support functions. One high TRL, already-flown example of such hardware that separates air and water is a Rotary Drum Separator [2]. A rotary drum containing a mixture of water and air spins very fast such that water is forced to the outer wall of the drum, and an air core is formed in the center. A tube located longitudinally in the center of the drum extracts the air, and an exit near the edge extracts the liquid water. This is currently on orbit on the ISS as part the Sabatier carbon dioxide reduction system used to produce oxygen for the crew. It uses 20 Watts of power nominally and 80 Watts peak power. It is quite noisy with requirements as "NC40 minus 3 dB for steady state, 72 dBA intermittent (<15 minutes per day)." Another commercially available phase separator is available from Advanced Cooling Technologies [3, 4]. This uses centripetal force of a rotating liquid rather than that of a rotating drum. The liquid/gas or liquid/vapor mixture is injected tangentially at the edge of the fixed drum. This high tangential velocity causes a swirling flow which results in the liquid remaining along the outer edge and the gas moving to the gas core via centripetal force created by the swirling flow. Another fixed technology development concept that separates air and water is the Static Phase Separator [5]. This application is for astronaut urine collection and subsequent separation for eventual disposal or use in a water recycler. This hardware has been tested in a low gravity environment aboard a parabolic flight, but not yet tested in a long term microgravity environment such as the ISS. An ISS flight experiment called Two Phase Flow Separator Experiment is under development at NASA [6]. Here the goal is to study the performance of a passive, inertia-driven swirl flow at the extreme limits of gas/liquid mixtures, and high and low flow gas/liquid rates. The flight hardware is scheduled to be available in 2020.

Static phase separation and capillary transport, such as used in the NC³, are not new concepts, having been investigated by a variety of researchers including the lead author [7,8]. Various approaches are available to use surface adhesion forces to drive liquid transport. In addition to hydrophilic and hydrophobic surface coatings aiding or replacing the innate surface properties of the materials of construction, capillary pressure gradients can be formed using changing dimension of the capillary structure. The integration of both inertial and capillary static phase separation with a condensing heat exchanger appears to be a novel approach. By using the moving air mass as the

driving force for inertial separation, the need for a mechanical phase separator is eliminated. Drag forces produced by the same air mass then serve to pull the condensed water along the outer wall of the condenser. Capillary forces on this same surface further aid in transport to the water collection volume.

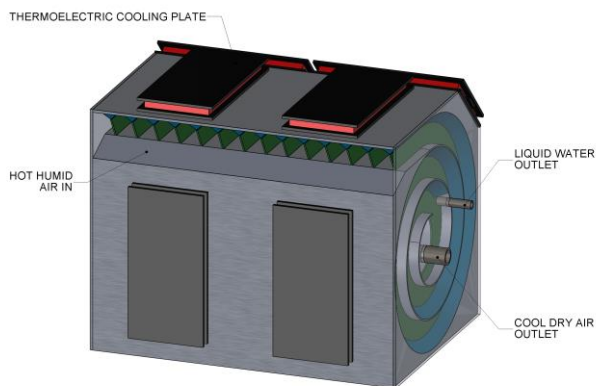
III. Initial Investigations

A conceptual drawing of an NC³ is shown in Figure 1. 1. Hot humid air enters near the top of the device. Liquid water forms via condensation on the cold condenser surface as the humid air passes along multiple parallel (stacked) spiral pathways. Cooling down to 1 °C is provided by thermoelectric coolers (TECs) or microgravity compatible heat pumps located on external surfaces of the NC³. Non-mechanical inertial forces are employed to transfer the liquid, as it forms, via centripetal action to the outer perimeter along each spiral path. A V-shaped groove channel constructed on this outer edge of the spiral geometry increases local capillary forces thereby retaining the condensate. The water is subsequently pulled along this channel by air drag, to a collection region near the center of the device. In an advanced configuration, a continuously varying V-groove dimension along the outer edge of the spiral path might be employed to create an effective capillary pumping force that would assist condensate transfer to the collection region.

Dry product air produced by each parallel spiral channel is combined in a common orthogonal, out-of-plane conduit passing down the axial center of the stacked separator. Similarly, the parallel water product streams are combined and removed from the separator through a separate out-of-plane axial conduit. Thus both the liquid condensate and the dry airstream are removed from the separator via distinct parallel pathways each perpendicular to the spiral planes. The resulting technology is an integration of conventional finned condenser operation, combined with non-mechanical phase separation and capillary transport phenomena. Liquid carryover into the exit airstream is minimized by a favorable geometric configuration in the terminal region of final collection/separation within each spiral plane. Here the momentum direction tends to carry the heavier water phase into a water exit port that extends in the same direction as the spiral flow path ends, while being at a right angle to the air exit port. In addition, by widening the flow channel and using an exit air port with a larger cross-section compared to the spiral cross-section, the gas velocity in this region is reduced thus minimizing liquid entrainment.

In our proof of concept work several quasi two-dimensional (single-plane) NC³ cells were fabricated and tested, as represented by those shown in Figure 2. These cells demonstrated a wide variety of mixed phase flow phenomena that were observed over the full range of air and water flow rates tested. In addition to the expected centripetal separation, other modes are observed. These include, as shown in Figure 2, plug flow (where water fills the entire cross-section of the flow channel), reverse centripetal separation (where the water collects on the inside of the spiral path), double-sided separation (where water covers both the inner and outer walls of the flow channel while the air flows down the center), and center channel separation (water occupies the center of the flow channel with air passing down along the walls on either side). Yet another case, similar to plug flow, occurs when water wets the aluminum bottom surface and air flow passes over the top between the water and the polycarbonate surface. Clearly, a complex interaction between cell geometry, material surface properties and operating conditions must be at play to account for such a variety in flow states.

Numerous inner separation geometries were also investigated that varied in construction detail relative to how the air and water phases were ultimately partitioned at the center of the cell. Many unique test cells exhibited good air/water separation over specific air/water flow operating ranges. In addition to separation, condenser operation was also demonstrated for a single-plane spiral flow path. Short visual recordings of a few of these devices under test have been uploaded as YouTube videos. [One](https://youtu.be/vC94LJ2M0LE) (https://youtu.be/vC94LJ2M0LE) of these videos contains a 3/32 inch thick, 1/2 inch wide silicone spiral operating at 5.0 SLPM air flow and 20 mL/min water flow. This test cell demonstrates good centripetal separation. [Another](https://youtu.be/GRoUcBNjIEc) (https://youtu.be/GRoUcBNjIEc) test cell that demonstrates good separation is constructed from 1/4 inch thick, 1/8 inch wide channels and operates at 2.0 SLPM air flow and 15 mL/min water flow. [A third](https://youtu.be/CNuJnPIs2f0) (https://youtu.be/CNuJnPIs2f0) video demonstrates the effective separation of air bubbles in a predominately water stream as they traverse a 1/8 inch thick, 3/4 inch channel width spiral test cell.



Nautilus Centripetal Capillary Condenser Concept

Figure 1. Conceptual NC³.

Note that the heavy, more dense, water occupies the outside of the curved flow path while the less dense air bubbles traverse the inner path as separated by centripetal forces.



Figure 2. Various flow phenomena: (Top Left) Plug flow; (Top Right) Reverse separation; (Bottom Right) Double sided; and (Bottom Left) Center separation.

IV. Circular NC³ Testing

A photo of a 5 inch diameter circular aluminum cell is shown under test in Figure 3. This separator was prepared with the inner spiral surface made fully hydrophobic by application a thin coating of the silicone material spread over the exposed edge of the sandwiched aluminum plates. In contrast, the outer edge of the spiral (where water is to collect) remained as uncoated aluminum thereby staying relatively hydrophilic.

As for previous designs, this cell was evaluated over a range of air and water feed rates. Performance of this device proved to be exceptional; see [5-inch separator link](https://youtu.be/Q6Jyf03Qzac) (<https://youtu.be/Q6Jyf03Qzac>). Even with the water initially introduced on the inner edge of the channel, as controlled by the positioning of a small tube inserted into the separator via the

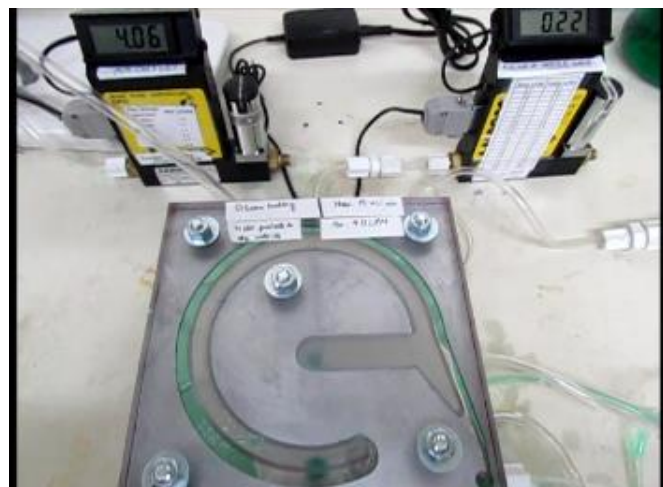


Figure 3. 5 inch aluminum circular separator under test.

water feed line, it was observed to rapidly transfer to the outer diameter and stay there for the remaining length of travel around the circular channel. Complete removal of the water phase with production of a water free air stream is ultimately observed in the region of terminal separation. In addition, attempts to upset the water stream (by physically shaking the separator) and cause a new steady-state flow path were unsuccessful. This desired separation state was therefore deemed to be robust and not easily disturbed. To further challenge the device's operation, the air flow rate was reduced to zero SLPM and the water input increased to 30 mL/min with the same 100% removal at the water collection port sustained. Capillary forces would appear to control phase separation for this device.

V. Integrated NC³ Testing

A condensing apparatus was prepared and tested to evaluate the second key feature of the technology: condensation of water from a humid air stream. The apparatus was made of four 'twelve-inch-by-twelve-inch' layers (described from top to bottom): i) a 1/2 inch thick polycarbonate sheet, used for observation purposes; ii) a 1/8 inch thick silicone spiral of 5/8 inch channel width; iii) a 5/8 inch thick aluminum condensation plate; and finally iv) a custom-built 5/8 thick aluminum cooling plate assembly, designed so that liquid coolant passing through the plate would cool the entire aluminum condensation plate down to, or below, 10°C. The spiral condenser is shown during testing in the center photo in Figure 4. On both the air and the water outlets, mass flow controllers were used to measure the amount of air leaving each outlet. Water exiting either outlet was captured by its own double-layer water trap system. This configuration allowed complete data recording of both air and water totals collected at each outlet. A digital psychrometer was used to measure dew point temperature of the air after leaving the condensing apparatus. Rather than immediately at the condenser's air outlet, the psychrometer was placed well downstream following the pair of water traps. This cell was evaluated under a handful of operating conditions, each representing some degree of supersaturation of water in an air stream (i.e., water vapor in excess of the saturation capacity of dry air at the operating pressure and temperature). The primary goal of this testing was to determine if the spiral design provides enough residence time in the condenser to drop the dew point of the exit air to the targeted level of 10 °C. Clearly, achieving this depends on several factors including air speed, channel size, channel length, actual condenser surface temperature, air mixing (for non-laminar flow) and/or water vapor diffusion (for laminar flow). In addition, these tests also served to allow verification of our method for the introduction of water vapor into the air stream feeding the NC³ separator. As indicated by the termination of the cloudy condensation layer on the left side of the

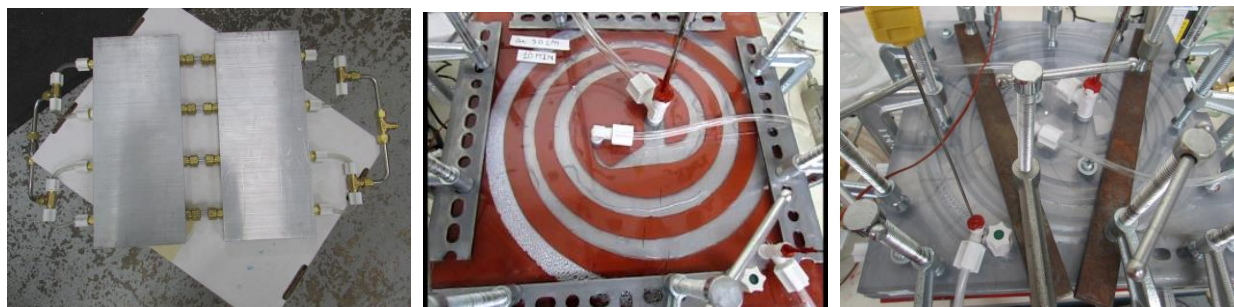


Figure 4. Integrated testing: Flow through cooling plates (Left Photo); Spiral condenser in operation with saturated water input (Center Photo); and Fully integrated NC³ in operation (Right Photo).

center photo in Figure 4, also [video link](https://youtu.be/kliZZxXsOqM) (<https://youtu.be/kliZZxXsOqM>), ending after approximately 180° half-turn of the spiral channel, dew point reduction to the cold plate surface temperature is readily achieved well before the air stream exits the device.

Using findings from all the cells tested prior to this, a fully integrated single channel NC³ condenser/separator was designed and fabricated in a 12 inch square configuration using polycarbonate and aluminum plates. The same terminal separation feature that was employed in the last several test cells was incorporated into this fully integrated design. The goal of this testing was to demonstrate concurrent operation of both the condensing and separation features of the NC³ technology. This fully integrated condensation/separation spiral cell is shown under test at the far right in Figure 4 while operating at an inlet air flow of 0.2 SLPM, a water input of 0.8 mL/min, and an air feed temperature of 91 °C. As in previous testing, water vapor mass flux was determined by measuring the weight change from the flask of heated water over the experiment duration. For this experiment a steady-state exit air dew point of 5 °C was observed. This is much better than the desired maximum 10 °C dew point for the device.

Additional testing with this device at the same air (0.2 SLPM) and a higher water feed rate (1.4 mL/min), with a consequentially higher inlet air temperature of 94 °C, still achieved a low 7 °C exit air dew point. Neither of these first tests was of long enough duration to observe separation in the terminal region of the separator, due to the relatively large system volume associated with the long spiral channel. Subsequent application of a silicone layer on the inner channel wall surface was performed to promote the same good separation demonstrated by the 5 inch aluminum circle separator. Ensuing tests with this integrated NC³, performed over a sufficiently long duration, indeed showed good condensation performance as well as 100% separation of the condensate under steady-state conditions. Furthermore, for steady-state operation, 71% of the inlet air stream was recovered in the dry air outlet of the fully integrated NC³ demonstration separator. The remaining 29% air stream assisted in final water removal from the separator with a small air flow required to support pressurized removal of water. In advanced NC³ designs employing negative pressure on water outlet side, hydrophobic coatings along the outer channel perimeter and novel channel cross-sections as shown in Figure 5 below, it is anticipated that this 29% value will be reduced to 5%-10%. In this event, a spiral separator similar to that employed in the third video link located at the bottom of page 3 of this paper could be used to good effect to further concentrate the air stream. At the very least mechanical centripetal phase separation remains available as an option to process this air/water mixed stream with the air burden having been significantly reduced by the NC³ condenser/separator. Ideally the remaining air/water mixed stream would consist primarily of water and a mostly liquid phase separator could be employed to maximum benefit [9].

VI. Advanced Designs

Technical work performed during the Phase 1 project included design, construction and evaluation of a variety of quasi 2-Dimensional (2-D) NC³ test cells. Observations and lessons learned during testing of these cells have enabled the preliminary design of serviceable 3-Dimensional (3-D) NC³ devices. Drawings of these designs were prepared in SolidWorks and are comprised of multiple layers of the 2-D spiral cells sandwiched together. The condenser/separator constructs for these designs are formed in two ways: i) using multiple stacked 2-D planes; as well as, ii) a true 3-D printed solid body device. Several possible channel cross-section shapes are under consideration, as represented by the shapes shown in Figure 5, each having no sharp corners on the inner wall of the separator channel.

In the advanced designs described below, a half circle is used for the inner channel surface and a simple straight line, fixed angle V-groove construction, is used for the outer edge of the channel. This shape corresponds to the geometry located in the lower right of Figure 5. A slowly changing V-groove angle along the spiral pathway will, however, ultimately be employed in advanced prototype design to drive capillary pumping. Many other channel cross-section shapes are conceivable and are to be evaluated in future work. A pseudo 2-D NC³ design that can be fabricated using conventional Computer Numerical Controlled (CNC) techniques is shown on the left in Figure 6. The primary advantage of this design is that the channel surfaces are exposed. During the machining process this means that the surface can be brought to the desired tolerance limited only by the tool. Direct access to the channel surface also means that hydrophobic or hydrophilic surface coatings can be applied at precise locations or on specific surfaces prior to assembly. Another advantage to this design is that the device can be disassembled, if needed, to modify the channel for evaluation of some new cross-sectional feature or surface coating. The main disadvantage to the stacked cell design is that many flat surfaces are required to contact and form leak free interfaces between each cell layer. This means that gasket seals must be applied between these layers, each a potential leak source. Ideally these seals would be fully captured/contained in their own machine grooves thereby allowing metal to metal contact between layers. These seals may also require that a significant amount of compressive force be applied to complete the final assembly. The metal to metal surface contact will also likely not be perfect (limited by surface flatness tolerances) and, as such, thermal conduction will be reduced in the overall body. Also, a potential disadvantage is the need to have a means to precisely line up the

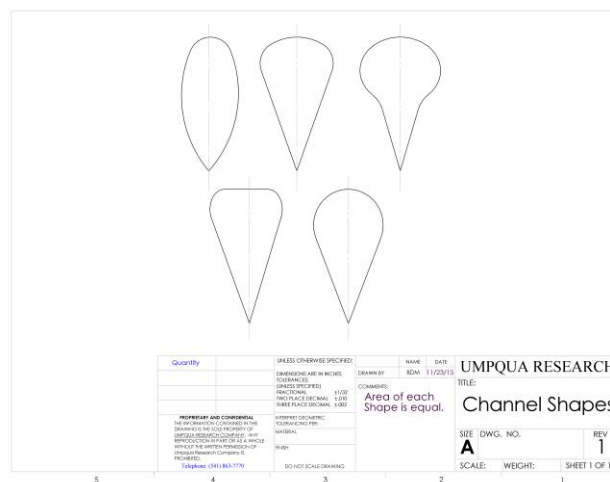


Figure 5. NC³ cross-section shapes of fixed length and area.

multiple plates during assembly so that all the edges match. This can be mitigated by employing multiple alignment pins/bolts or other mechanisms between each layer.

A 3-D printed NC³ design is shown on the right in Figure 6. This design has the distinct advantages of neither requiring gaskets between each layer nor is the final assembly particularly challenging. This design also has the advantage of allowing optimal heat transfer through a solid metal body with no interfaces or intermediate gasket material to limit thermal conduction. Disadvantages include the inability to directly polish or shape the printed channels to exact tolerances. Also, 3-D printed surfaces, particularly those produced by metal printers, are typically rougher than those that are machined. Another disadvantage is that any type of surface coating that imparts a

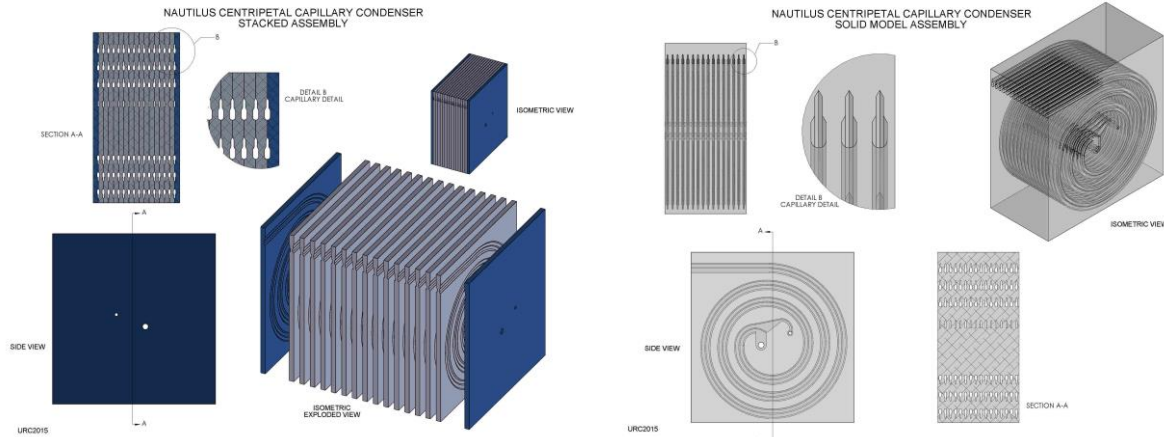


Figure 6. 2-D stacked (Left Image) and 3-D printed (Right Image) advanced NC³ designs.

hydrophobic or hydrophilic nature is very difficult (maybe even impossible) to apply to specific surfaces on the internal cavern structure within a finished solid 3-D object.

VII. Future Work

Both of the advanced designs described above are to be finalized early in follow-on work with the desired channel cross section shape employed. They will be subsequently fabricated and comparison tests executed to define any performance differences. The results of these tests should greatly guide design of subsequent NC³ condenser/separators. By iteration of design / modeling / fabrication / testing, over the course of this future development work, a well refined design will result. The work will begin by taking the results and lessons learned during the proof of concept phase, reported here, to improve both the performance and scale of each element. This work will culminate in design, fabrication and testing of deliverable prototype hardware sized according to NASA's needs. Necessary design features will be incorporated insuring safe operation of the prototype and thereby meeting or exceeding the safety requirements of the NASA center where it will ultimately undergo independent verification testing. Ostensibly, there will be design improvements identified during this testing that will necessitate the fabrication of an even higher fidelity device. Presumably, this device will then serve as an excellent baseline design in support of an ISS flight experiment to evaluate the NC³ condenser / static phase separation technology under microgravity conditions. The ultimate goal of this investment will be to establish a safe, robust, low mass, energy efficient NC³ technology that NASA can utilize during future manned deep space exploration missions.

As far as scaling the condenser to a practical level of operation is concerned, the NC³ design tested here has been shown to attain the desired 10 °C dew point while operating at water vapor mass flows up to 1.4 g/min. Note that this water flux is approximately 19 % of that produced by a Heat Melt Compactor (0.2 SLPM of dry air and 7.5 mL/min water) at peak operation [10]. Or similarly a water flux at 18 % of that for a humid air stream such as that which might be found in a cabin Air Revitalization system. For example, humidity within the cabin or water vapor produced by the Carbon dioxide Reduction Assembly [11,12]; the latter potentially generating a 95 °C saturated air stream at 2 SLPM (2 SLPM x 3.3 mL water/ g air x 1.2 g air/L air = 7.9 mL/min). Note that in these applications a nominal 5.5 scale-up is required above that demonstrated by the proof of concept NC³ device in this Phase 1 effort. Because of the modular (stackable/parallel) nature of a NC³, this should simply equate to adding five more parallel spiral channels as portrayed by the advanced designs discussed above.

VIII. Conclusions

In summary, our proof of concept work consisted of fabrication and testing of several quasi two-dimensional, single channel NC³ cells. These test cells were challenged over a variety of air and water flow rates to define viable operating ranges that exhibit good air/water separation for each unique cell design. In addition to separation, condenser operation was also demonstrated for a single channel spiral flow path. Our experimental work culminated in the design, fabrication and testing of a fully integrated single channel condenser/separator cell demonstrating operation near a 20% scale compared to that required for a practical device employed aboard a manned Mars transit mission. Lastly, with application of lessons learned during testing, advanced multichannel designs were prepared for future fabrication and evaluation in an advanced development effort.

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